An Ontology to Represent Firefighters Data Requirements During Building Fire Emergencies[I]

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Abstract. Firefighters require accurate and timely information regarding a building and its environment to perform their duty safely and successfully during a fire emergency. However, due to the chaotic nature of building fires, firefighters often receive erroneous, conflicting, or delayed information that can affect the outcome of an emergency. In this paper, we propose a solution in the form of an ontology that defines building and environmental data needed by firefighters during a building fire emergency. The ontology development followed the METHONTOLOGY method and was implemented using the web ontology language (OWL) in Protégé 5.5.0. Built-in reasoners in Protégé and an ontology pitfall scanning tool were employed to verify the structure and consistency of the new ontology. To validate the ontology efficacy, we developed a prototype web application to represent and visualise relevant information based on the ontology and used that as a basis for conducting interviews with firefighters. Finally, a specification document that describes the ontology was created and published online. The proposed ontology can be a basis for developing intelligent tools and systems that collect building and environmental data from different sources and provide comprehensive information to firefighters. It can also facilitate the data exchange process between the different personnel involved in emergency response activities. In addition to emergency service providers, the ontology can also support building and city planners during the design and operational phase of buildings and city facilities. It can help them understand how fire service providers interact with different building and environmental elements. They can use that understanding to produce and maintain design outputs that reflect firefighters' data requirements. Furthermore, automated data-checking tools can be built based on the ontology to ensure the availability of essential data for firefighters in building and city-scale datasets. Building control bodies can use such systems to perform conformity checks that ensure design outputs deliver the needed data.

Keywords: Ontology, building fire response, firefighters, data requirements

1. Introduction and Motivation

Fire hazards in buildings can bring fatal consequences to occupants and incur considerable property damage. Building fires are also hazardous to the firefighters who risk their lives to provide emergency services. Firefighters may face fatal injuries during fire suppression operations and rescue efforts (Fahy, Petrolli and Molis, 2019). Therefore, they employ different strategies to safeguard occupants, reduce property damage, and protect themselves during building fires.

Firefighters devise their strategy based on the best available information at any given time (OSHA, 2015). Hence, the availability and quality of information play a vital role in the outcome of an emergency. Faster access to information will enable first responders to comprehend the emergency quickly and respond appropriately. It can also increase the safety of building occupants and firefighters as well as reducing property damage (OSHA, 2015).

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Firefighters should be aware of any hazards or obstacles they may encounter outside or inside the affected building ahead of time. Simultaneously, avoiding information overload is also essential to reduce difficulty and confusion in data collection and interpretation (Li et al., 2014). The success of a firefighting strategy relies on providing the correct information and resources to the right people at the right time (Xu and Zlatanova, 2007).

However, acquiring and communicating accurate and timely information during a fire emergency is challenging. Occupational safety and health administration (OSHA, 2015) provides insight into the difficulties firefighters face when gathering information at an incident site. According to OSHA (2015), firefighters have a frequently changing workplace which is an emergency site. Therefore, they are unlikely to know their next workplace ahead of time. Furthermore, they operate in a mentally stressful environment while performing physically exhausting work that makes collecting, interpreting, and communicating information challenging. Moreover, they may need to operate at night or in harsh weather conditions, with possible reduced visibility due to smoke from the fire. In such conditions, firefighters find it difficult to fully comprehend their environment and gather information from different signs that are used to communicate valuable information. The challenges are further magnified in complex building structures such as high-rise buildings and underground structures. Any delay caused by these issues might adversely affect the subsequent operation and the overall outcome of the incident. Mishaps such as poorly located fire hydrants, unclear fire alarm information, or inaccessible equipment can result in a delay during which the fire likely grows and becomes more hazardous to occupants' and firefighters' lives (OSHA, 2015).

Solutions to the problems discussed in the previous paragraph could be provided through intelligent tools and systems that collect relevant data about an affected building and its surrounding from different data sources and provide comprehensive information to firefighters. Such intelligent tools and systems can assist firefighters in conducting their tasks with the utmost safety and effectiveness (Balding, 2020). The design of such systems requires a well-defined understanding of firefighters' data requirements.

Well-defined data requirements will assist in integrating different data sources and form a comprehensive knowledge about an incident site to support the decision-making process taken by first responders (Li et al., 2014). It will also facilitate the data exchange process through various mediums between the different personnel involved in the emergency response (Jones et al., 2005). Understanding how first responders interact with building features can also assist building designers in designing structures that ensure firefighters' safety and provide necessary firefighting features (OSHA, 2015). With such understanding, building and city planners can ensure their design outputs contain the needed data for fire emergency response activities. A structured data requirement definition can also be used to develop data-checking systems for targeted datasets. For instance, a model checking tool for a building model can ensure the model contains all relevant data for firefighters. Such systems can be used by building control bodies to carry out conformity checks that ensure design outputs deliver the data needed by emergency providers. The same system can be designed for city-scale datasets. Municipalities or other parties responsible for maintaining city data can ensure they have the essential data first responders require during an emergency response.

This research proposes an ontology that represents firefighters' data requirements. Ontologies can be used to establish a structured understanding of a given domain. They enable us to develop machine-understandable definitions of different concepts in a given domain along with their relationships and allow us to develop intelligent tools and technologies (Noy and McGuinness, 2001). Through ontologies, a shared understanding of a domain between people and systems can be established (Neto et al., 2021). The new ontology we developed represents the data firefighters require regarding different elements and features inside an affected building and its surroundings.

The paper is structured as follows. Section 2 discusses existing ontologies related to building fire emergencies and identifies gaps that a new ontology can address. Section 3 presents the method we employed to develop the new ontology. Section 4 provides a detailed discussion of the ontology we developed, named *Firefighters' Data Requirements (FFDR)* Ontology. Section 5 discusses the steps we took to evaluate the ontology, including prototype development and expert interviews. The section also covers the development of a specification document for the ontology. Discussions and conclusions are provided in Sections 6 and 7, respectively.

2. Related Works

Studies on building emergency response operations have shown first responders' heavy reliance on peoples' experience, memory, and observation to gather information during fire emergencies (Li et al., 2014). This reliance could bring negative consequences. Firefighters operate in a stressful environment (OSHA, 2015). They may find it hard to observe and communicate information accurately under stressful circumstances. Furthermore, human memory might introduce human errors (Li et al., 2014). Mishaps in gathering and communicating information can adversely affect the outcome of an emergency (OSHA, 2015). Intelligent tools and systems that assist first responders in gathering and communicating essential information can be a part of a comprehensive approach that supports first responders. A comprehensive approach that provides essential information to first responders can improve the effectiveness and success of emergency response processes (Jones et al., 2005).

Adapting new approaches and technologies for firefighting should be done with great care since firefighting is a potentially dangerous job (Balding, 2020). Therefore, having a well-defined understanding of firefighters' data requirements is essential to developing tools that ensure safety and effectiveness. Ontologies are one method of creating such understanding. Ontologies can establish a shared understanding of a domain between people and systems (Neto et al., 2021). We can define a set of data and their structure through ontologies, which can then be used by different problem-solving tools, applications, and systems (Noy and McGuinness, 2001).

2.1 Existing Ontologies for the Fire Emergency Domain

Several ontologies have previously been developed for the emergency domain. Some ontologies focused on the general representation of concepts related to wide-ranging crisis events. For instance, an ontology named *DoRES* was built to assist in data collection and reporting during crisis events (Burel et al., 2017). The intended users were government organisations, non-government organisations, and individuals. However, the use of this ontology for building fire emergencies is extremely limited since it is a relatively simple and general model that is meant to be applied to a wide variety of crises. It does not represent concepts specific to fire emergencies or firefighters' data requirements. The model needs to be extended in order to be used for a particular crisis. Another study by Rauch and Fox (2017) defined three ontologies to represent relevant information regarding emergency response, fire brigade organisations, and death related to fire or natural disasters. The first ontology (emergency response ontology) was developed to represent the process involved during an emergency. The emergencies identified were fire emergency, medical emergency, and police emergency. The information captured about the emergencies includes location, time, cause, severity, speed, impact and involved actors. Another ontology named *empathi* was also defined to model core concepts in the domain of emergency management during a crisis (Gaur et al., 2019). It provides representation for hazard type, phase, impact, and location. The ontology can facilitate real-time disaster monitoring by assisting in the automatic recognition of disaster-related data mentioned in social media conversations.

A few ontologies were developed with more focus on victims and affected communities rather than first responders. For example, the *SEMA4A* ontology was developed to assist in communicating emergency notifications to diverse categories of people using several technologies during different emergencies (Malizia et al., 2010). The ontology was letter extended with concepts related to communicating the accessibility of evacuation routes to people during emergencies (Onorati et al., 2014). Gang Liu et al. (2011) developed an ontology focused on community-based fire management. The ontology represents concepts concerning the mitigation, preparation, response, and recovery phase of fire management. However, it only represents those concepts at a high level, and it is aimed at the affected community.

In some ontologies, the focus was put on the emergency providers, including firefighters. However, in these ontologies, the emergency was not mainly focused on building fires. Examples of this include the emergency management ontology that was defined to relate the different organizational units (police, fire brigade, municipality, and medical centre) involved in emergency response with the data they require (Fan and Zlatanova, 2011). The ontology focussed on spatial data, although it required emergency responders, including fire brigades, to have their own ontology representing their specific geospatial data requirements. It also associated the emergency units with the process they participate in during an emergency. We also have another ontology that was developed and implemented to establish a common vocabulary between team members (humans and robots) during urban search and rescue efforts (Saad, Hindriks and Neerincx, 2018). The ontology captured knowledge regarding the human and robot actors, their capability and role, their task, their communication system, and important environmental objects and events that are necessary during search and rescue.

We have also identified a group of ontologies explicitly focused on emergency scenarios in buildings. For instance, an ontology by Nuo et al. (2016) was developed to generate a semantic graph of a building in times of fire emergency. The graph could then be used to obtain smoke spread information and escape routes. The ontology aimed to support rescuers and victims during the rescue process. Another example is an ontology named *EmergencyFire*, which was defined to support the standardisation and sharing of building fire response protocols (Bitencourt et al., 2018). The ontology models the procedures and actions taken during a fire emergency, and rovides terms that can help describe the emergency. It also captures knowledge regarding the involved organisations, the resources they can deploy, and their communication methods. However, a detailed representation of knowledge regarding building features and building surroundings that are important for firefighters' operation was absent since it was outside the scope of the ontology. We also have another ontology developed by Neto et al. (2021) to assist the information exchange between the different parties involved in the building evacuation process during fire emergencies. The authors believe the ontology helps to understand the building evacuation domain and contributes to the development of applications and systems that can be used during building evacuation. Finally, we have the *Smart Building Evacuation Ontology (SBEO)* which represents knowledge regarding buildings and their occupants that can be useful for safely evacuating people during emergencies (Khalid, 2021).

2.2 Research Contribution

Overall, several ontologies with concepts that can apply to building fires have been developed in the past. Some provided only a general representation by focusing on top-level disaster management. A few others focused on victims rather than first responders. In some ontologies, the focus was on the first responders, but the emergency scenario was not focused on building fires. Some ontologies explicitly focused on building fire emergencies. They described concepts related to hazard description, firefighters' actions, and building evacuation. However, the representation of data needed by firefighters regarding building features and the building's surroundings was minimal and outside the scope of those ontologies. Therefore, we propose an ontology that can fill that gap.

The ontology we present in this paper provides a detailed and comprehensive representation of the data firefighters need about several features and components of an affected building and its surroundings. Based on this new ontology, intelligent systems and technologies that collect and provide essential data to firefighters can be developed. The ontology can also be used to facilitate the data exchange between the different personnel involved in building fire emergency response activities. Additionally, the knowledge captured in the ontology can be used to develop ontology-based data-checking systems for building and city datasets. These systems can be used to ensure essential building and environmental data is available to firefighters. They can be implemented during the design phase of a building as well as for compliance checking.

3. Research Approach

To develop our ontology, we followed the METHONTOLOGY method proposed by Fernandez et al. (1997). METHONTOLOGY is a well-structured method for developing ontologies from scratch. The consecutive phases of the method we followed are:

- Specification,
- Conceptualization,
- Integration,
- Implementation,
- Evaluation, and
- Documentation

During these development phases, knowledge acquisition was also conducted simultaneously. Figure 1 presents the consecutive development phases and their outputs. Each phase is discussed in the following sections.

Knowledge Acquisition: The knowledge captured in the ontology was gathered from the analysis of the following sources:

- A study conducted by Li et al. (2014) with 29 first responder participants to evaluate firefighters' information needs during a building fire emergency response,
- A study by Isikdag et al. (2008), where data requirements for a successful fire response management operation were identified,
- A workshop conducted by the National Institute of Standards and Technology (NIST) with 25 participants on the information need of first responders (Jones et al., 2005),

- Multiple studies regarding environmental factors that influence the spread of fire (Ghodrat et al., 2021)(Santarpia et al., 2019)(Heron et al., 2003),
- A manual published by OSHA that provides detailed information regarding firefighters' typical interaction with building features and fire protection systems during fire hazards (OSHA, 2015).
- NFPA 1620, A standard for pre-incident planning developed by the National Fire Protection Association (NFPA) (NFPA, 2020)
- The international building code (International Code Council (ICC), 2018a) and
- The international fire code (ICC, 2018b).

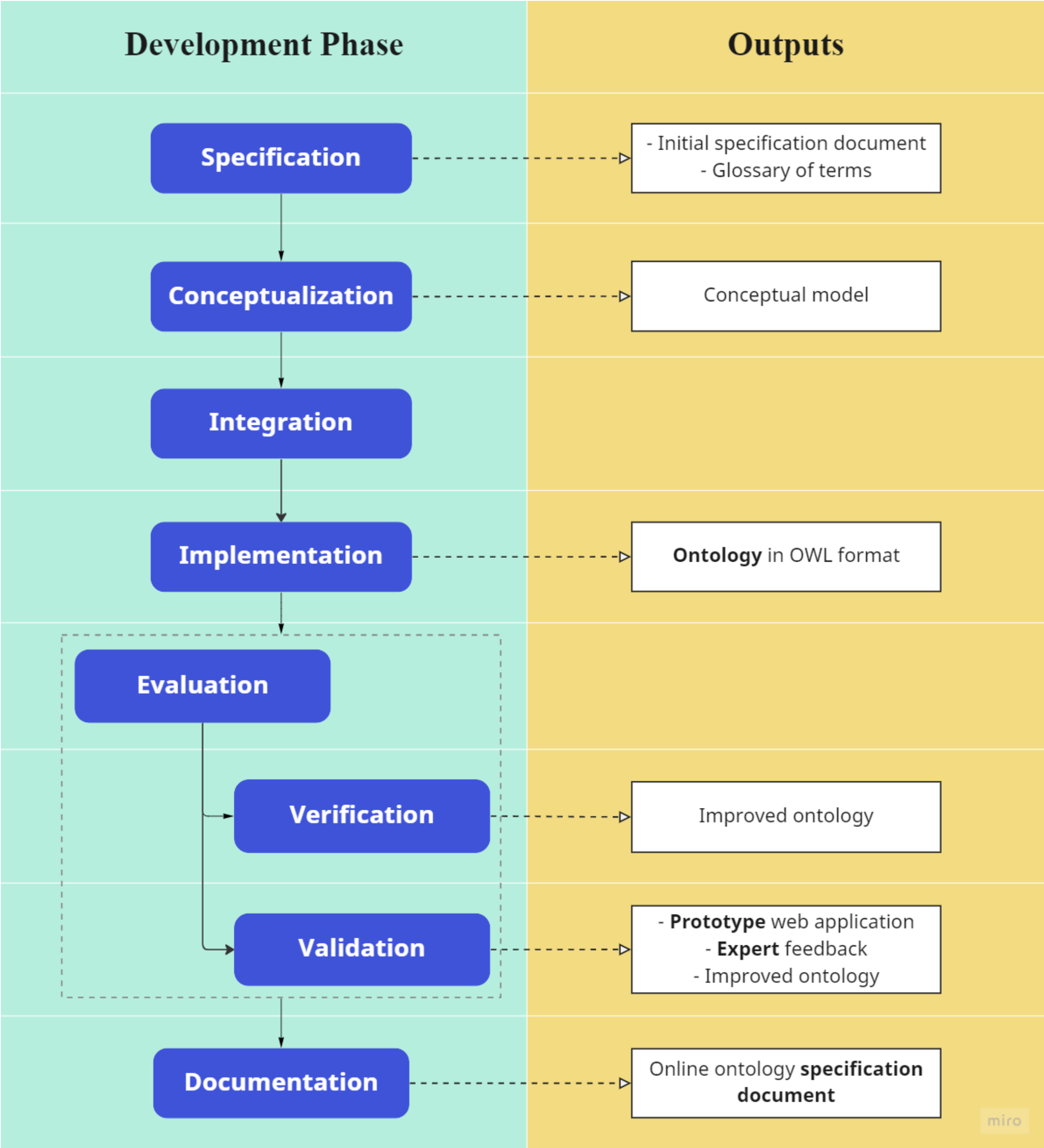


Figure 1: The ontology development phases and their outputs.

Specification: a specification document is prepared in this phase of the ontology development. The document specified the purpose and scope of the ontology and its intended use (see Table 1). A glossary of terms that should be included in the ontology was also prepared. This action continued with the subsequent phases as more knowledge was acquired. The glossary of terms allowed tracking of terms that needed to be modelled and ensured they were not missed (Fernandez, Gómez-Pérez and Juristo, 1997). It was also helpful to filter out synonyms or irrelevant terms.

Table 1: Ontology specification document.

Requirements	Descriptions
Domain	Building fire emergency
Purpose	Building an ontology to represent data regarding several features and components of a building and its surroundings that firefighters need when responding to building fires.
Scope	The focus is on data about an affected building, its different components, and its surrounding.
Intended use	The ontology can be a basis for developing tools and systems that gather essential data about a building and its surroundings and provide the collected data to firefighters in an integrated form. The ontology can be used to develop ontology-based data checking systems for building and city datasets (i.e., building and city-scale design, operational and maintenance data). It can also facilitate the data exchange process between different personnel involved in emergency response.
knowledge source	Scientific papers: (Li et al., 2014), (Isikdag, Underwood and Aouad, 2008), (Jones et al., 2005), (Ghodrat et al., 2021), (Santarpia et al., 2019), and (Heron et al., 2003). Manual: (OSHA, 2015). International codes: (NFPA, 2020), (ICC, 2018a), and (ICC, 2018b).

Conceptualization: In this phase of ontology development, knowledge is structured in a conceptual model (Fernandez, Gómez-Pérez and Juristo, 1997). First, the glossary of terms created in the specification phase was completed. These terms represented different concepts and their properties acquired through knowledge acquisition. A middle-out approach was used to identify the terms. As Fernandez et al. (1997) pointed out, this approach first identifies primary concepts that need to be represented in the ontology. Then, based on necessity, the concepts could be specialized or generalized. International codes were used whenever possible to generate concise and consistent terms that others can reuse in the future (see Table 1 for the international codes). The terms in the glossary were grouped into classes, properties, and instances. Finally, relationships were established between the terms.

Integration: Reusing existing ontologies was considered in this phase to facilitate the development of the ontology (Fernandez, Gómez-Pérez and Juristo, 1997). Reusing would reduce the effort needed to create the ontology from scratch. Section 2 discussed existing ontologies in the emergency management domain. We explored possibilities to reuse part of some of those ontologies. We also examined ontologies outside the emergency management domain. However, the ontologies we inspected had a different focus and scope than our proposed ontology. Therefore, we could not directly reuse those ontologies. Any reusing would require extensive modification to the structure of those ontologies. That would impede the ontology development process and prevent us from accurately expressing the concepts we aim to represent. Therefore, we decide not to reuse those ontologies. However, some of the ontologies have complementary scopes with our ontology. Hence, they could be connected to expand the breadth of representation. The discussion section (Section 6) will expand on this further.

Implementation: The next phase in the ontology development was implementing the ontology in a formal language. The web ontology language (OWL) was selected to implement the ontology. OWL can represent the meaning of terms and the relationship between terms in a machine-interpretable language. Protégé 5.5.0 (Musen, 2015), an open-source application, was used as the development environment to create the OWL file. The following section will describe the ontological model we named *Firefighters' Data Requirements (FFDR)* Ontology.

4. Firefighters' Data Requirements (FFDR) Ontology

The *Firefighters' Data Requirements (FFDR)* Ontology represents concepts regarding the data firefighters need about an affected building, the building's features, and the building surroundings. Several classes were created to represent different concepts in Protégé. Some of these classes have a hierarchical relationship which was represented using a subclass relationship. Most of the classes had multiple properties and relationships with other classes. OWL provides the *ObjectProperty* feature to represent the relationships between two classes and the *DatatypeProperty* feature to represent the relationships from a class to a data value (McGuinness and van Harmelen, 2004). We have used both features extensively in the ontology.

In this section, the ontology is described with the help of figures (Figures 2 – 4). In the first two figures, the following convention is used. Red boxes emphasize a class, and yellow boxes represent all other classes related to the classes in red boxes. Different lines are used to represent different relationships. Solid lines with a black `is a` text indicate subclass relationships. Solid lines with blue text indicate *ObjectProperty* relationship between classes, and broken lines with green text indicate *DatatypeProperty* relationship from a class to a data value. The deep purple blocks indicate instances of a class. Sometimes a thick black arrow is extended from a class to indicate the existence of more information that is not shown in the figure. A yellow box with three dots is used to indicate the existence of more subclasses.

4.1 Incident site

The ontology uses the *IncidentSite* class to represent the site where the building with fire hazard is located. This class is shown in a red box in Figure 2. The class is related to *IncidentBuilding, SurroundingTerrain, SurroundingStructure, FireCommandCenter,* and *WeatherCondition* classes. The *IncidentBuilding* class represents the building where the fire hazard occurred (See Section 4.2). The terrain and structures surrounding the incident building are represented by the *SurroundingTerrain* and *SurroundingStructure* classes, respectively.

The *FireCommandCenter* class represents a dedicated location or room in a building (or nearby a building) where the status of fire protection systems, alarms, and other emergency systems can be monitored and controlled (ICC, 2018b). Incident commanders need to locate and access this room to use the centralized command capability it provides. The information needed to locate and use this space is modelled in the ontology.

The *ControlPanel* class represents the different control panels firefighters would want to locate and use to control several building systems and utilities. These systems and utilities include fire alarm systems, building utilities (such as power supply, gas supply, and water supply), mass notification systems, and smoke control systems. These control panels could be located inside a fire command centre or other areas. The *ControlPanel* class has properties that specify the location and description of the control panels.

The *IncidentSite* class is also related to the *WeatherCondition* class, which represents weather-related information firefighters may want to know. Wind speed and direction can affect the spread of fire and smoke (Ghodrat et al., 2021). It may even spread the fire to surrounding buildings, vegetation or other flammable objects and cause even more destruction. Other weather components, such as air temperature, relative humidity, and precipitation, can also affect how the fire hazard unfolds. A fire hazard that occurs on the same site but during different weather conditions could have different effects and outcomes (National Wildfire Coordinating Group (U.S.), 1994). Therefore, these weather components were represented in the ontology as properties of the *WeatherCondition* class.

The *SurroundingStructure* class represents all artificial and natural structures surrounding the incident building. Information about surrounding structures such as powerlines, pipelines, hazardous materials, and obstructions is essential since they can obstruct firefighting operations or even cause severe injuries to firefighters (OSHA, 2015). Fire can spread from the incident building to its surrounding through vegetation. Hence, the vegetation surrounding an incident building is represented using the *Vegetation* class. A *fire lane* is an access road designated for the passage of fire apparatus (ICC, 2018b). This class is also a subclass of the *Road* class

Fire hydrants are essential for most fire suppression operations since they provide access to a water supply system. We modelled information that should be provided to firefighters in advance to locate and rapidly connect to a fire hydrant. The *FireHydrant* class is related to two classes representing water sources and hose connections. Accurate information about hose connection type and size should be provided to firefighters because incompatible hose connections can create severe problems during firefighting operations (OSHA, 2015). The *HoseConnection* class is also connected to all other concepts in our ontology related to some form of hose connection.

An adequate water supply is essential for firefighting since most fire suppression systems and operations are water-based (OSHA, 2015). Therefore, we created a *WaterSource* class to capture relevant knowledge regarding water sources during a fire emergency. Under this class, two subclasses were defined that represent municipal distribution systems and static water sources (such as lakes, ponds, swimming pools, etc).

Two classes are not part of the incident site but could still be considered as concepts outside of the affected building. One of them is the *RoadToIncident* class (subclass of the *Road* class) which represents the road that leads to the incident site. The other is the *EmergencyServiceProvider* class which represents fire service organisations, hospitals, and police departments.

4.2 Incident building

Several information requirements about the incident building are modelled as properties of the *IncidentBuilding* class. A complete list of the requirements can be seen in Figure 3. The figure also shows the relationship between *IncidentBuilding* and other classes. These classes include the *BuildingOccupancy* class, the *BuildingComponent* class and the *ConstructionType* class. The *BuildingOccupancy* class represents a building's occupancy based on the international building code (ICC, 2018a). The *BuildingComponent* class represents information about the different components of the building (see Section 4.3). The *ConstructionType* class is modelled with its five instances. These instances or types are given by the International Building Code (ICC, 2018a). The construction type depends on the materials used in the building (whether they are combustible or non-combustible) and the fire resistance of the building elements. The *IncidentBuilding* class is also related to the *Address* class, which captures several types of addresses required during a building emergency.

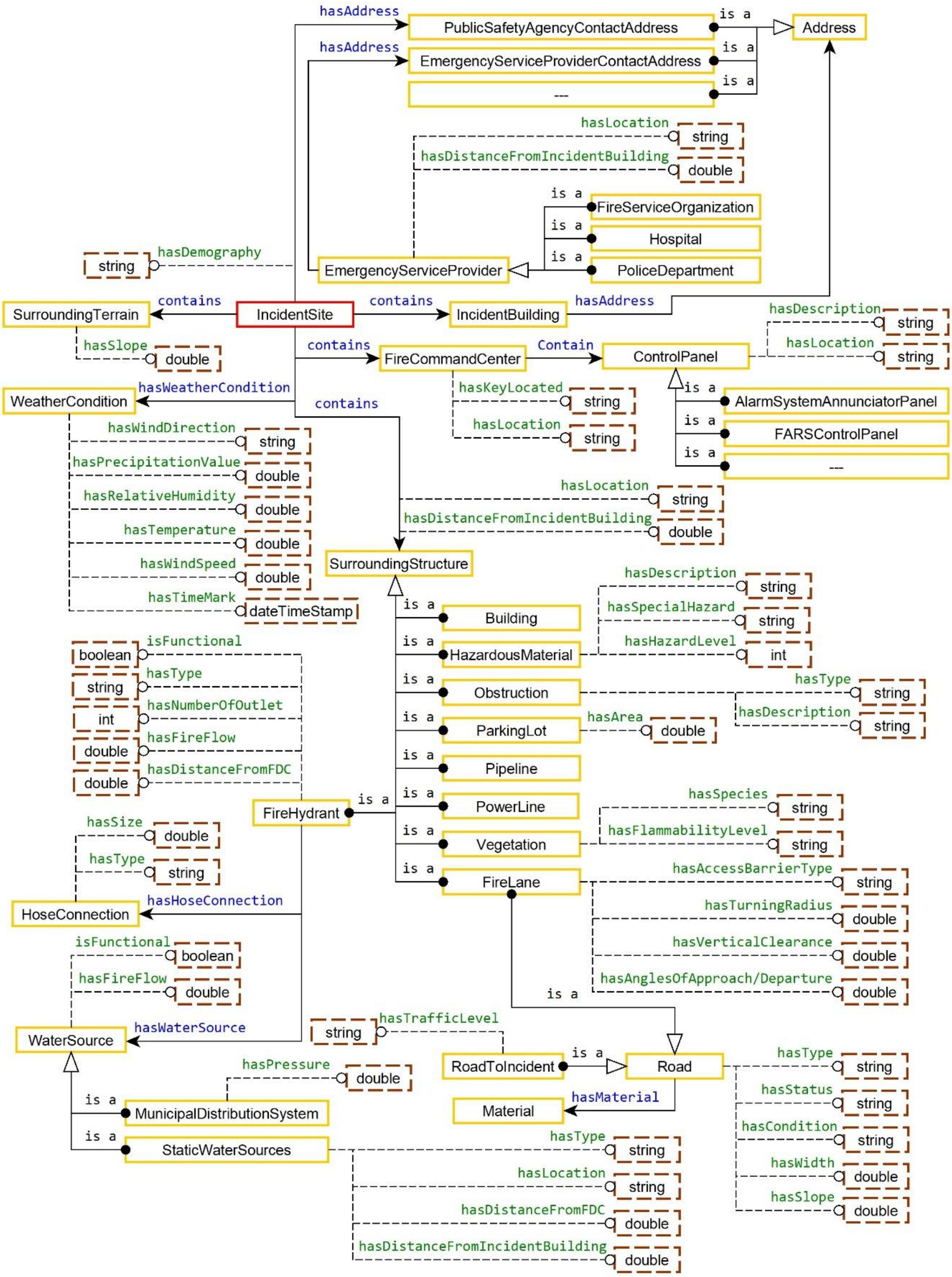


Figure 2: The *IncidentSite* class, its properties, and its relationship with other classes.

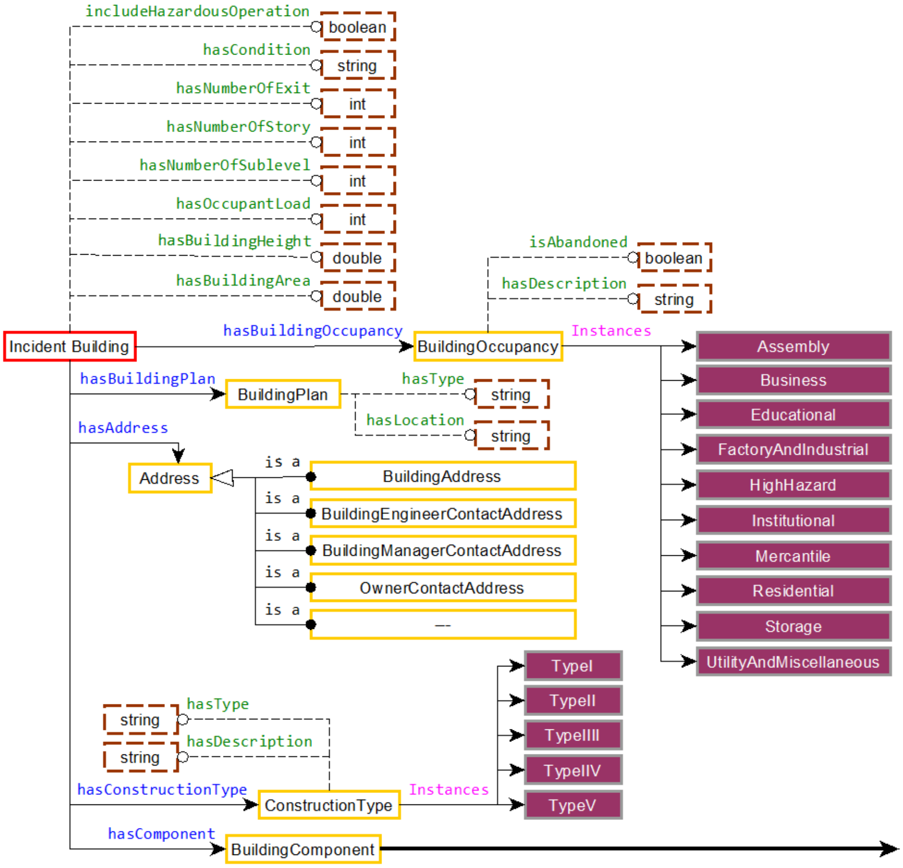


Figure 3: The *IncidentBuilding* class, its properties, and its relationship with other classes.

4.3 Building Component

As buildings get taller or larger, more portions of the building will be beyond the reach of ladders, and external firefighting options will be limited or unavailable (OSHA, 2015). Hence, firefighters will be required to enter such hazardous buildings with limited escape options. In such cases, the internal components of the building will become more significant. In the ontology, these components are represented by the *BuildingComponent* class. The *BuildingComponent* class has several subclasses representing different building elements and systems firefighters interact with during their operations (see Figure 4 (A)). *BuildingSafetySystem* is the largest subclass of *BuildingComponent.*

4.3.1 Building safety systems

Several subclasses are defined for *BuildingSafetySystem* that capture information about the different fire safety systems found inside buildings. The complete list is shown in Figure 4 (B). An automatic fire extinguishing system refers to a sprinkler system or another automatic fire extinguisher system installed in a building. In most buildings, a sprinkler system is separated into coverage zones (OSHA, 2015). This information is valuable to firefighters because the fire can be located based on the active sprinkler zone. The Fire alarm system and other sensors and detectors are also divided into different zones.

A standpipe system is a system of pipes in a building that provides water for manual firefighting and, in some cases, for sprinkler systems (OSHA, 2015). A fire department connection (FDC) is an inlet through which firefighters feed water into the standpipe system. In contrast, fire hose connections (FHC) are outlets of the standpipe system inside the building where firefighters can connect their fire hoses (OSHA, 2015). Firefighters need to know both connections' location and connection type for interior fire suppression activity.

The *BuildingSafetySystem* class has more subclasses that represent other building safety systems. Some of these systems are: (based on Occupational Safety and Health Administration (2015)).

- An emergency power outlet built into a building can provide power for electric-operated firefighting equipment,
- Firefighter air replenishment system (FARS) filling stations or panels allow firefighters to replenish their breathing apparatus cylinders,
- Mass notification systems allow firefighters to provide instructions to building occupants,
- Smoke control systems help to protect building occupants while they evacuate the building,
- Smoke and heat removal systems assist firefighters in removing smoke after a fire is extinguished,
- Fire and smoke protection elements (i.e., Fire barriers, fire partitions, firewalls, shaft enclosures, smoke barriers, and smoke partitions) serve to protect firefighters during a fire emergency in addition to the building occupants, and
- Fire pumps are used to boost the water pressure to standpipes and sprinkler systems.

These systems and elements have properties relevant to firefighters. All these properties are modelled in the ontology.

4.3.2 Other Building Components

In addition to safety systems, firefighters may interact with other building components, which are also captured in the ontology. Some of these components could facilitate firefighters' operations. For instance, key boxes (small vaults placed in the building or nearby containing keys to the building's doors, elevators, and other equipment) are essential for firefighters because they eliminate the need for forced entry which would take extra time (OSHA, 2015). Meanwhile, other components could be detrimental to firefighters and their operations. One example of such components is unprotected vertical openings, which are highly hazardous to firefighters since they might be working in dark or smoky conditions (OSHA, 2015). The different utilities that may be found in the building (such as the water or the gas supply system) usually need to be shut down or at least controlled during fire emergencies to prevent hazardous situations to firefighters (OSHA, 2015). Firefighters should also be informed of the location and type of any hazardous material they may come across in the building.

Information regarding the façade of an incident building is essential for firefighters. It could be used to predict the spread of fire to the surrounding buildings or other structures. Some rooftop elements could be helpful in some firefighting operations but can also cause hazards. For instance, skylights can be used to ventilate a building but can also cause firefighters to fall through (OSHA, 2015).

Limited information about structural and non-structural building elements is modelled in the ontology to not overload firefighters with excess information. OSHA (2015) describes how building elements could assist firefighters or sometimes cause a hazard. Doors, hallways, stairways, and in some cases, elevators are essential during egress. Meanwhile, floor and roof assemblies made with lightweight construction members could collapse and injure firefighters. The complete list of the non-structural elements (subclasses of *NonStructuralElement*) is given in Figure 4 (C).

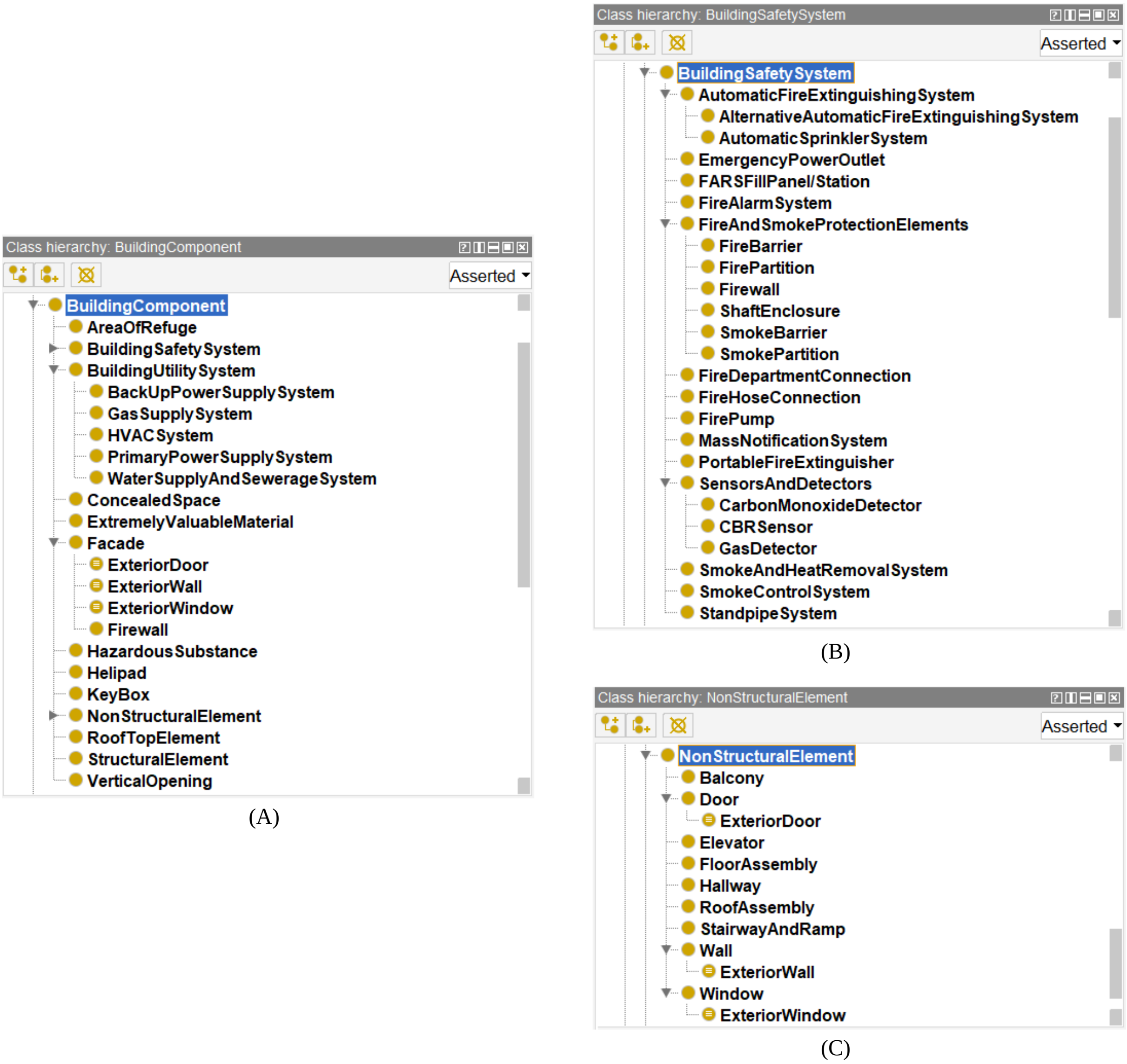


Figure 4: Subclasses of (A) *BuildingComponent* class, (B) *BuildingSafetySystem* class, and (C) *NonStructuralElement* class.

5. Ontology Evaluation and Documentation

The next phase of ontology development is evaluation. The evaluation phase covers the verification and validation of the ontology (Fernandez, Gómez-Pérez and Juristo, 1997). According to Fernandez et al. (1997), verification is the technical process that confirms the correctness of an ontology, while validation is the process that confirms whether an ontology corresponds to the concepts it was modelled to represent. The following two sections will cover the steps taken to verify and validate the *FFDR* ontology.

5.1 Ontology Verification

This phase entails the evaluation of the correctness and consistency of the new ontology. The first part of the evaluation proceeded with the help of Pellet (Sirin et al., 2007) and HermiT (Glimm et al., 2014), which are OWL reasoners available within Protégé (the ontology development environment). The reasoners allow us to identify conflicting assertions in our ontology and verify whether the restrictions we set are satisfiable.

Reasoning on our ontology with Pellet and HermiT identified a few inconsistencies. These inconsistencies were due to malformed logic. For instance, some inconsistencies occurred due to the use of the *disjointWith* construct. This construct is applied to classes to assert that an instance of one of the classes cannot be an instance of the rest. The reasoners identified cases where this assertion caused inconsistency in the ontology. We asserted that most of the top-level classes are disjointed. The *Road* class and the *SurroundingStrucure* class are one of those superclasses. However, the two classes have one common subclass: the *FireLane* class (See Figure 2). Hence, an instance of a *FireLane* class will be an instance of both *Road* and *SurroundingStrucure* classes. This conflicts with the *disjointWith* assertion we made. Therefore, we fixed this inconsistency by removing the *disjointWith* assertion between the two classes and instead applied it between the *SurroundingStrucure* class and the subclass of the *Road* class, excluding the *FireLane* class. Likewise, the ontology underwent other modifications that resolved all the inconsistencies in the ontology.

After the reasoners, *Ontology pitfall scanner!* or *OOPS!* was used to verify the ontology further (Poveda-Villalón, Gómez-Pérez and Suárez-Figueroa, 2014). The tool maintains a catalogue of common pitfalls often found in ontologies. At the time of this writing, the catalogue has 41 recognised pitfalls. Ontologies checked by this tool will be analysed based on this pitfall catalogue. The tool identified multiple pitfalls in our ontology. These pitfalls were the following:

- Creating unconnected ontology elements.
- Merging different concepts in the same class.
- Missing annotations.
- Missing domain or range in properties.
- Inverse relationships not explicitly declared.
- Using a miscellaneous class.
- Using different naming conventions in the ontology.

The ontology underwent further modifications to address the errors identified by the pitfall scanner. We repeated these verification processes every time we modified the ontology to ensure the changes did not introduce any inconsistencies and errors.

5.2 Ontology Validation

For the validation phase, a prototype application was developed based on the ontology and was used to conduct interviews with firefighters. The usefulness of the ontology was evaluated through these interviews. The following sections discuss the prototype development, the expert interviews and the results of the validation phase.

5.2.1 Prototype Development

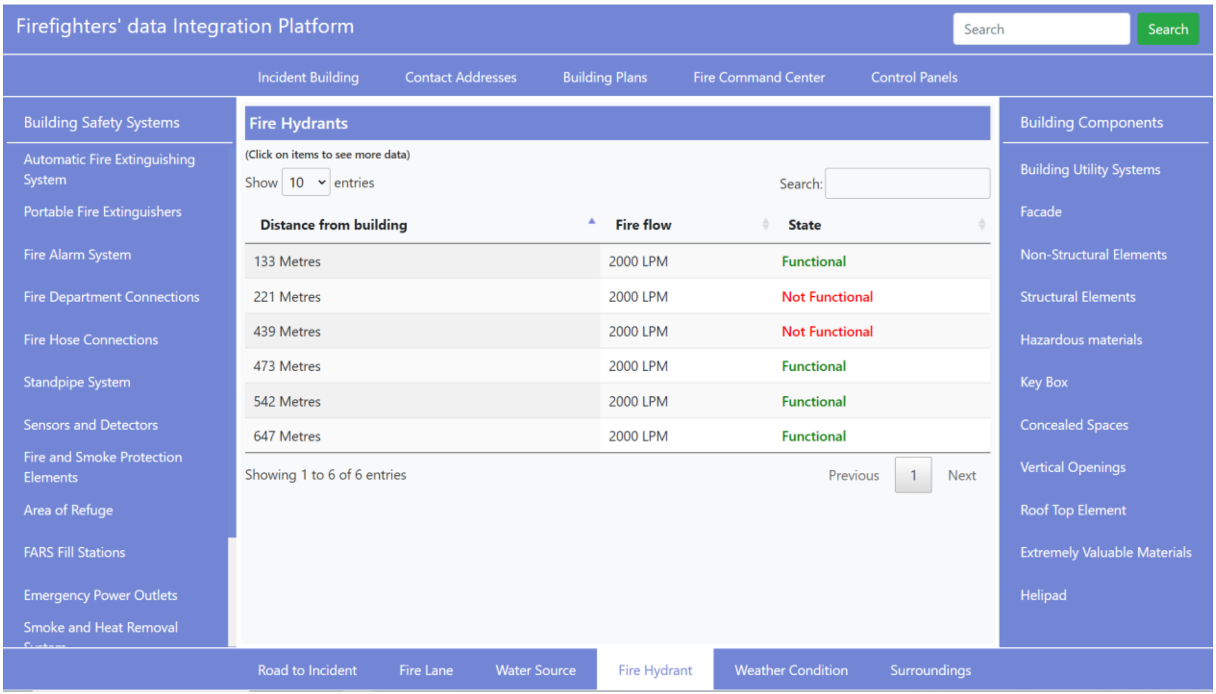
The prototype[III] is a web application that represents and visualises relevant information based on the ontology. It was developed using the *Django* framework. The framework was selected because it enables the rapid development of web applications. A python script was written to migrate all classes along with their properties and hierarchical relationships defined in the ontology from OWL to *Django* classes and fields. *Owlready2* (Lamy, 2017), a python module for ontology-based programming, was used in the python script to parse the ontology from OWL format.

The prototype's user interface (UI) was developed to be simple and straightforward. All classes from the ontology are available in the form of menu options on navigation panels. In most cases, users only need to click once to get to a certain data. Sometimes, users may need to click a second time to get additional data. This simplicity was essential to running the interviews smoothly. It made it easy for users to understand the application regardless of their background knowledge and skill regarding software systems. It also prevents users from being distracted by application features and instead focus on the data it provides, which is essential to evaluate the concepts captured in the ontology. Moreover, it also considers the situation in a real emergency where clear and straightforward access to data is required.

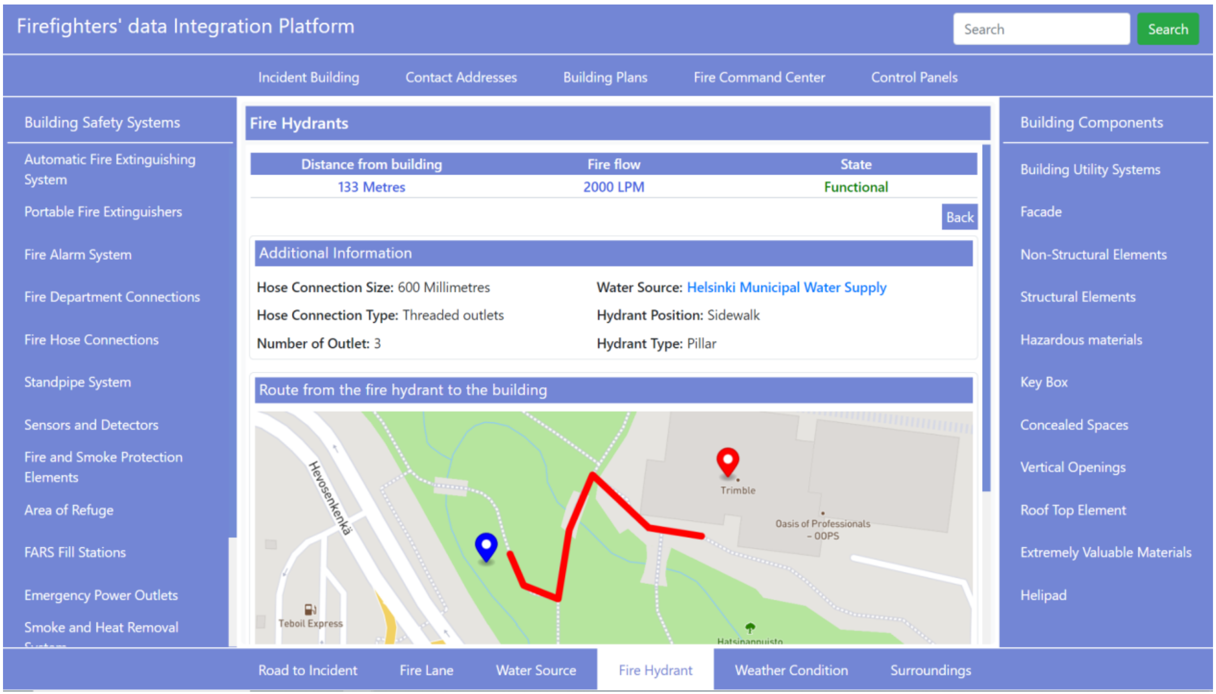
After the prototype was complete, it was ready to be populated with data. A thirteen-floor office building in Espoo, Finland, was selected as a case study. Building and environmental data for this selected building was collected according to the proposed ontology. A combination of real and generated data was used for demonstration purposes. This data was stored in a cloud *MongoDB* database and served as the data provider for the prototype web application.

The prototype is a data integration platform for firefighters. It represents building and environmental data about a selected building that is relevant for fire emergency response. Figure 5 presents a screenshot of the application. The application displays information at the centre. The items on the menu surrounding the centre and the search feature are used to find and view specific data. All menu items, including submenus, are classes from the ontology. When clicked, they retrieve class instances from the database. Each instance can have multiple pieces of information about a specific concept, represented as class properties in the ontology. For instance, in figure 5 (A), the `Fire Hydrant` menu is selected, representing the *FireHydrant* class in the ontology. Six fire hydrants close to the affected building are listed at the centre of the screen. These are six instances of the *FireHydrant* class found in the database. For each fire hydrant, distance from the affected building, fire flow, and whether it is functional is presented. These are properties of the *FireHydrant* class. When an item from the list is selected, more information is revealed, as shown in figure 5 (B). All additional information pieces are properties of the *FireHydrant* class.

[III] The prototype is available at https://www.ffdiplatform.com/



(A)



(B)

Figure 5: The prototype web application that was developed based on the ontology for the validation phase.

5.2.2 Interviews with Firefighters

We conducted interviews with firefighters to analyse the performance of the ontology in accurately representing firefighters' data requirements. The prototype and the building case study described in the previous section were used in these interviews. Four firefighters with a long year of fire response experience were involved in these interviews. Two participants were from Finland, the third was from Germany, and the fourth was from Norway. The interviews were focused on two topics. The first topic was firefighters' data requirements, while the second topic was about existing data sources currently in use during emergency response activities. The latter discussion is outside the scope of this research; hence it will not be discussed in this paper. The discussion regarding data requirements was used to validate the ontology and will be discussed in the following sections.

During the interviews, we asked the participants to assume there was a fire at the building selected for the case-study. The firefighters were asked to assume they were called to respond to a fire emergency at this building. Then, they began describing the response process focusing on their data requirement. The discussion covered the period from the beginning of a fire hazard until it is taken under control. The firefighters listed several pieces of information they needed during that time.

During the interviews, the data the participants requested were noted. The aim was to check the availability of the data in the prototype. Hence, a list of data requirements was created after each interview based on the participant's responses. Some items were removed from these lists because they dealt with concepts outside the scope of the ontology. For example, data about the fire, the victims, and vehicles were removed since the scope of the ontology is building and environmental features (See Section 3). After the interviews were concluded, all the data requirement lists were merged by removing repeated items. The result was 46 unique data requests.

Out of the 46 data requests put forward by the participants, the prototype was able to provide answers to 40 queries. Some of the questions that were answered by the prototype (hence represented in the ontology) are the following:

- What is the building used for?
- How many floors does the building have?
- How many people could be in the building?
- Is there hazardous material in the building?
- Is the building covered by a sprinkler system?
- Which alarm is activated?
- Where are the entrances to the building?
- Where are the fire hydrants located?
- Where are the fire department connections located?
- What is the wind direction?
- What is the connection type of the fire hose connections in the building?
- Where are the smoke ventilations located?
- What is the traffic condition on the road leading to the incident building?

However, there were six requests the prototype could not provide, indicating that some concepts needed to be added to the ontology. Modifications were made to the ontology to address the issue. The six missing concepts (and one additional issue identified during the modification) and the resulting modifications are given in Table 2.

Table 2: Modification of ontology to address missing concepts.

Missing concepts in the ontology	Modifications to ontology
Building's year of construction	A new datatype property labelled *hasYearOfConstruction* was created for the *IncidentBuilding* class.
Parking area in the building	A new class labelled *ParkingArea* is created as a subclass of *BuildingComponent* class. The new class has *hasLocation*, *hasCapacity* and *hasNumberOfParkedCars* datatype properties. The *hasCapacity* property can be used to specify the number of cars a parking area can hold. The *hasNumberOfParkedCars* property can be used to represent the number of cars parked in the parking area during an emergency. While this data is useful in itself, it can also be used to estimate the number of occupants.
Restricted area in the building	A new class labelled *RestrictedArea* is created as a subclass of the *BuildingComponent* class. Two datatype properties are created for this new class: *hasLocation* and *hasDescription*. Description regarding how to access the restricted area can be provided using the *hasDescription* property.
Nearby buildings occupancy	The ontology already contains the *Building* class as a subclass of the *SurroundingStructure* class to represent buildings near the affected building. To address the question of occupancy type of surrounding buildings, the *Building* class is related to *BuildingOccupancy* class using *hasOccupancy* object property. A new datatype property labelled *hasLandUse* is also created for the *IncidentSite* Class. This property can represent the human activity at a given site, including the incident building and surrounding buildings.
Operating smoke ventilations	Smoke ventilation systems are represented in the ontology using the *SmokeandHeatRemovalSystem* class. In order to include a description of how to operate the system, the *hasDescription* datatype property is added to the *SmokeandHeatRemovalSystem* class.
Hazardous operations in the building	*HazardousOperation* class is created to represent possible hazardous operations in a building such as moving machines and radioactive devices. The class is then related to data type properties *hasDescription*, *hasLocation* and *hasType* in order to represent essential details about hazardous operations. A *hasHazardousOperation* object property is also created to relate *IncidentBuilding* class to the new *HazardousOperation* class.
Additional modifications regarding hazard representation	After observing the effect of the previous modification on the ontology, a *Hazard* class is created to represent all types of hazards. Then the *HazardousOperation* class and *HazardousMaterial* class are collected as subtypes of the new *Hazard* class. In this manner, hazard-related concepts are aggregated together along with their properties.

The verification phase was repeated after the changes listed in Table 2 were made to the ontology to ensure the modifications had not introduced errors. With these checks, the validation phase was concluded.

5.3 Documentation

The documentation phase refers to documenting each step of the development process, which has been done in this research paper. We also created and published an online ontology specification document. The document can be accessed using the ontology's internationalised resource identifier (IRI). The IRI that identifies the ontology is https://purl.org/ffdr-ontology. The document provides an overview and description of the ontology. It also includes a description of all classes, properties, and instances, along with annotations. The document also includes the ontology file in different file formats. There are two versions of the online documentation at the time of writing this paper. The first version is the original ontology before the validation phase. The second and latest version is the ontology after it is improved through expert feedback during the validation phase. We used *Live OWL Documentation Environment (LODE)* (Peroni, Shotton and Vitali, 2012) and *Wizard for documenting ontologies (WIDOCO)* (Garijo, 2022) services to develop the documentation.

6. Discussion and Future Activities

The main contribution of this research is the development of a firefighters' data requirements ontology. Existing ontologies in the fire emergency domain provide minimum to no representation of firefighters' data needs about a building and its environment. The ontology developed in this paper addresses this lack of representation. It comprehensively represents data about a building and its surroundings that firefighters require during a building emergency.

The ontology captures building components firefighters interact with during an emergency response. Some of these components are building safety systems. In contrast, others are not safety-related components but are still relevant for firefighters' operations. Additionally, building components that could pose a danger to firefighters, such as hazardous materials, openings, and obstacles, are also represented in the ontology. Outside the building, the ontology represents environmental elements that are relevant during a fire emergency response. Some of these elements are useful for fire suppression activities, such as access roads and fire hydrants. In contrast, other elements can potentially obstruct firefighting operations, cause danger to firefighters and contribute to fire spread. All these elements and their relevant properties are represented in the ontology. The information represented in the ontology will help fire responders quickly comprehend the emergency. Access to information will assist firefighters in devising a response strategy that safeguards the building occupants, protects the firefighters and reduces property damage (OSHA, 2015).

Using the data requirement established in the proposed ontology, we can begin to investigate possible digital data sources that can be used for fire emergency response. The data represented in the ontology spans multiple domains such as building, city, traffic, road, water distribution and weather. It also combines static data with dynamic data. For instance, the area covered by a sprinkler system is static data. In contrast, whether the sprinkler is currently active or not is dynamic data. Possible data sources include Building Information Models (BIM) that can provide data about building elements, features, and systems. Different Internet of Things (IoT) solutions can provide dynamic data about an activated fire alarm system, sprinkler system, or gas detectors. Similarly, city models can provide the city-level data requirements defined in the ontology. Dynamic data about weather conditions and traffic levels can be collected from several web services through Application Programming Interfaces (API). Future research that identifies and examines these data sources in detail can support the utilization of the ontology in the real world.

It is reasonable to expect the data sources for the requirements identified in the ontology to be heterogeneous since they span different domains. Future research activities can use the proposed ontology to map and integrate these heterogonous data sources. Such data integration can support the development of data integration platforms for firefighters where all required data can be accessed. A prototype web application developed for this research demonstrated what a future data integration platform for firefighters might look like (Section 5.2.1). Similar tools can be developed based on the ontology that gather and provide comprehensive data to firefighters. These tools can assist firefighters in conducting their life-saving activities safely and successfully.

Aligning the new ontology with existing ontologies in the building and city domain can facilitate its utilisation. Some examples existing ontologies include the Building Topology Ontology (BOT) (Rasmussen et al., 2020), ifcOWL (Pauwels and Terkaj, 2016) and Brick schema (Balaji et al., 2016) from the building domain and CityGML ontology (Vinasco-Alvarez et al., 2020) from the city domain. Future research could investigate these and other similar ontologies and align them with the proposed ontology. Another possible direction for further research is integrating the new ontology with existing ontologies in the emergency management domain. For instance, the emergency management ontology defined by Fan and Zlatanova (2011) requires the different units involved in emergency response, including fire brigades, to have their ontology representing their geospatial data requirement. Our new ontology can be integrated with the emergency management ontology to represent fire brigade data needs. Similarly, our ontology which describes the building and surrounding features can be integrated with the *EmergencyFire* ontology (Bitencourt et al., 2018), which describes the responding unit's organisation, resources, and tasks. Section 2 provides further discussion about existing ontologies in the emergency domain.

The proposed ontology can also benefit people and organisations responsible for creating, maintaining, and checking building and city-scale datasets. It can help building designers understand how firefighters interact with different building elements and features. As a result, the designers will know what data to include in their building design outputs. During the operational phase of a building, several types of building data are generated and maintained by facility managers. The proposed ontology can help facility managers identify what data is essential during building emergencies, including information about building systems such as sprinkler systems, alarm systems, gas sensors and ventilation systems. Similarly, at a city-scale level, the ontology can also help city planners and municipalities understand the emergency providers' needs concerning city-level data.

Automated rule-checking systems can be developed based on the ontology for building and city-level datasets. Building designers and facility managers can use checking systems to ensure the availability of essential data for firefighters in their dataset. Building control bodies can also employ a checking system based on the ontology to perform conformity checks focused on fire safety. Beyond buildings, the ontology can be used to check city-scale datasets and information about fire hydrants, vegetation, water bodies and road networks.

We identified two limitations of the research. One is the limited number of expert interviews conducted to evaluate the ontology. However, this is compensated to some level by the literature used to develop the ontology. Two of the literature analysed discussed workshops that were conducted to identify information needs during emergency responses (Li et al., 2014) (Jones et al., 2005). Several first responders, including firefighters, participated in these workshops. Twenty-nine first responders participated in the workshop by Li et al. (2014), while twenty-five first responders attended the workshop by the National Institute of Standards and Technology (NIST) (Jones et al., 2005). The output of these workshops and other literature were used as a source of knowledge for the ontology development (See Section 3). However, to further increase the involvement of firefighters, more interviews can be considered for the future.

Another limitation of the ontology is the diverseness of firefighting activities and data requirements based on region and country, which was observed during interviews with firefighters. The participants in the interviews were from different countries. While most of the data requirements they identified were similar, there were also a few differences. Some data deemed necessary by a particular participant was less important or, sometimes, unneeded by another participant from a different country. We decided to keep concepts identified as necessary by at least one participant in the ontology. As a result, some of the concepts modelled in the ontology may not be relevant for some firefighters based on their country of operation. As a remedy, a submodule of the ontology can be created for a particular region with concepts that are relevant to that specific region.

The proposed ontology is geared towards fire hazards in buildings. It provides a representation that can apply to a wide variety of building types, including residential, commercial, and industrial buildings. However, if required, a specialization of the ontology can be developed by focusing on a specific type of building. Furthermore, the concepts defined in the ontology can be adapted to other types of crisis events that occur within a city where combined information about buildings and their environment is required for crisis management. Examples of such events include earthquakes, floodings, terrorism, and hurricanes. Understanding the data required to manage these events can help digitize the response process and improve outcomes.

7. Conclusion

We introduced the *Firefighters' Data Requirements (FFDR)* ontology in this research work. The ontology models relevant data regarding a building, its features, and its surroundings that are essential for firefighters' operation during building fires. The ontology was built using the METHONTOLOGY method of ontology development. The ontology was checked for correctness using reasoners and an ontology pitfall scanning tool. Its usefulness was evaluated by developing a prototype web application and conducting interviews with firefighters. After verifying and validating the ontology, a specification document that describes the ontology was created and published online along with the ontology.

The proposed ontology can be used to identify potential digital data sources for fire emergency response and to devise a data integration framework that integrates these data sources. Hence, it can be the basis for developing systems that collect building and environmental data from various data sources and provide comprehensive information to firefighters. Such systems can support firefighters during building fire emergencies to make decisions that safeguard occupants, protect the firefighters themselves, and reduce property damage. The ontology can also facilitate the data exchange process between different personnel involved in emergency response in addition to firefighters. It can also be used to develop ontology-based data-checking systems that ensure the availability of essential data for firefighters in building and city-scale datasets. They can also be used throughout the life cycle of a building or facility to ensure that required data is always maintained.

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